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A wireless inertial measurement system (WIMS) for an interactive dance environment

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Abstract: This paper will present the work carried out in designing a Wireless Inertial Measurement System (WIMS) designed for a wearable system operating in an interactive dance environment. The concept underpinning this system is the generation of inertial information from multiple nodes distributed over a dancers body, which will enable the dancer to communicate with their environment and interact with their surroundings through movement. The IMU nodes will be arranged in a network configuration whose control will be based upon existing technology developed at Tyndall.

1 Introduction

A lot of work has been carried out in the area of interactive arts in the responsive environment group out of MIT Media Lab [1]. The work reported on included systems using magnetic sensors for Tangible Music Interfaces [2] and processing algorithms for large groups of dancers using wireless networks. The Interactive dance concept at Tyndall was developed in conjunction with an artist who had worked with interactive vision systems such as the Very Nervous System developed at Brown University [3]. She felt that a transition to onboard sensors would yield a new era in interactive performance art. Many sensor arrays were investigated such as proximity through ultrasonic systems, touch through conductive or piezoelectric sensors and motion through inertial sensors. Motion/orientation was decided as the core sensing capability required so a wearable Inertial Measurement System was the first system to be designed.

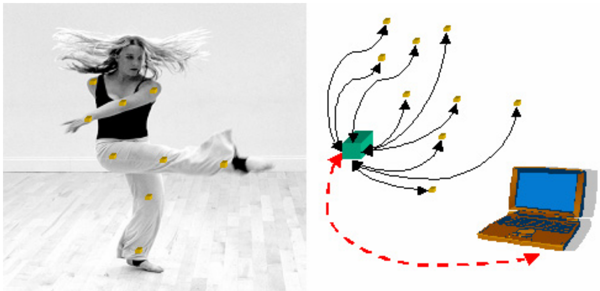

Figure 1. Deployment concept and high-level architecture of the WIMS system.

2 Technology Development

The 25mm wireless sensor network platform developed by Tyndall's MAI group is a low volume prototyping and experimentation platform. It has been developed for use as a platform for sensing and actuating, for use in scalable, reconfigurable distributed autonomous sensing networks in a number of research projects currently underway in the in the centre [4]. The platform is a 'plug and play' system that currently employs FPGA technology, wireless transceiver technology and embedded microcontroller technology [5]. These sub-systems make up the core of the platform allowing for the development of customized sensor layers using the control and processing capabilities integrated into 25mm cube. The 25mm cube platform is shown in figure 1.

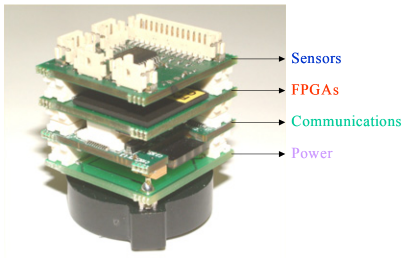

Figure 2. 25mm Platform.

An inertial measurement unit has been developed to connect to this 25mm platform to validate the IMU system architecture for further minimisation and to test and characterise the unit [6]. This system architecture has then been migrated to a 10mm platform level using bare die sensors and innovative flexible substrate technology developed at Tyndall. The 10mm modules will be wirelessly enabled and capable of communication with the 25mm module. The 25mm Master will be capable of querying the slaves in order to retrieve the inertial data, configure and reconfigure the network. This Master Unit will act as a gateway to the higher level processing algorithms which will be running on an off board system. This off-board system will interpret the information sent from the dancer and control the environment accordingly.

2.1 25mm Inertial Measurement Unit (IMU)

The system architecture is made up of multiple inertial and magnetic sensors, analog to digital conversion and processing/control hardware. The high-level architecture of the module is shown in figure 3.

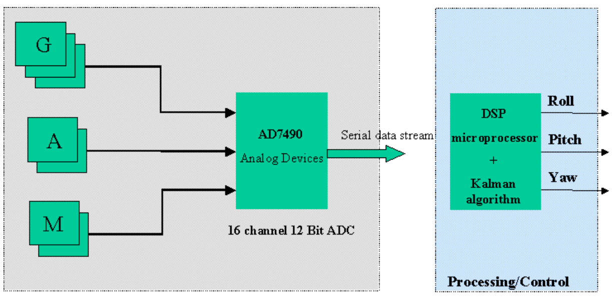

Figure 3. IMU Architecture

The MEMS sensors used in this design are Analog Devices parts. The ADXL202JE is a two-axis accelerometer, which is available in a miniature LCC package. The ADXRS150 is a single axis gyro, which meant the system had to integrate three such sensors to achieve a 6 Degree of freedom IMU. The HMC1052L, which is a miniature Magnetometer produced by Honeywell, is also integrated in to the design. This combination of sensors was decided upon to provide multiple sources of information for the possible implementation of a Kalman filter on the 25mm FPGA layer.

2.2.1 Integration of IMU

For any IMU, the orientation of the inertial sensors is very important and the sensor axes need to generate a 3-axis system. This, consequently, means the sensors need to be arranged in an orthogonal array and at 90° to each other. For this reason the system required two accelerometers, two magnetometers and 3 gyroscopes. The design of the IMU was based on a concept using a motherboard containing slots allowing the connection of daughter boards at 90°. Three different boards were subsequently designed - a daughter board containing an accelerometer and a magnetometer, a daughter board containing a gyroscope and a motherboard capable of accepting two of each of the daughter boards at 90° to each other. The motherboard also contains the third z-axis gyroscope, signal conditioning circuitry, AD conversion and connection to the processing/communication layer. The accelerometer board and the 90° interconnection technique are shown in figure 4.

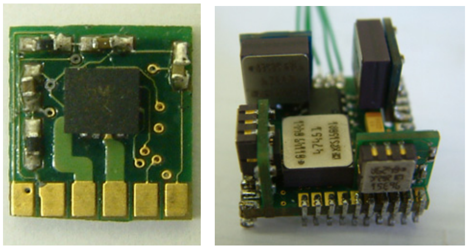

Figure 4. IMU board Designs and interconnect technique.

Each of the sensor boards was manufactured with a thickness of 1mm under tight tolerance control. The motherboard was manufactured with 1mm slots milled out of it to receive the sensor boards and connect to the conditioning circuitry. The conditioning circuitry included the passive components for the sensors and buffering circuitry for the analog signal lines before analog to digital conversion.

2.2 10mm Inertial Measurement Unit

The 10mm IMU is a miniaturisation of the 25mm system using bare die sensors and a flexible substrate. This flex substrate is employed to maintain the orthogonal array the sensors by bending the flex at right angles. The process flow for the implementation of this module was devised from a set of experiments involving the integration of the bare die and the flex substrate. The 10mm unit has a number of revisions planned with the initial design connecting two 10mm cubes together, which is known as ‘the berries’. One of these modules will consist of the sensor system and the other will contain the RF and power systems. The next revision of the system will involve the integration of the two cubes in to a signal 10mm cube to produce a wirelessly enabled 10mm IMU. Figure5 shows the concept of the 10mm berries connected using a low profile FFC connector.

2.2.1 Bare Die Sensors

The sensors used in this design are the Analog Devices sensors described earlier. The bare die sensors are new protected using a capping technique developed at the Micromachining Lab in Analog Device [7]. The MEMS structures are covered by a silicon cap, which provides a lot more opportunity for encapsulating and packaging the sensors. This was developed to allow for miniature injection moulded Lead Frame Chip Scale Packages (LFCSP) to be developed and released on the market.

2.2.2 The Design

The process for connecting the bare die to the flex is based on a concept of drilling a hole in the flex and flip chipping the die face down to the flex. Attaching the chip to the substrate is done using Anisotropic Conductive Film (ACF), Anisotropic Conductive Adhesive (ACA) or micro solder bump interconnect on the chip. The entire circuit is designed on a single sided flex substrate in the form of a cross. This cross structure can then be folded to yield a six-sided cube, which provides the orthogonal array as shown in Figure 5. This process is based on work carried out previously at Tyndall [8].

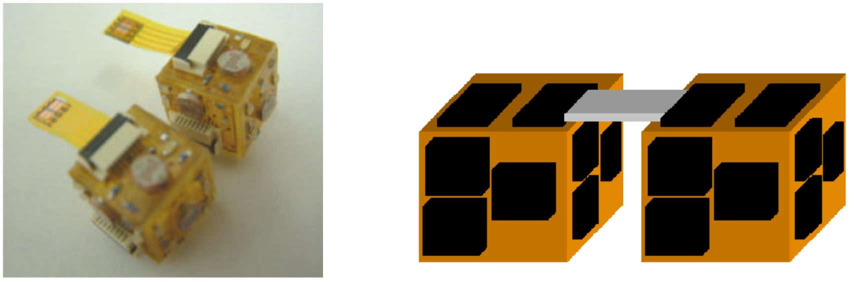

Figure 5. Assembled Flex cubes and Berries concept

The 10mm design is still in its early stages and a test vehicle structure is being developed with two bare die accelerometers mounted on a flex substrate. This will yield a test structure for the validation of the process and lead on to the development of the fully functional IMU. Early results showed that the hole drilling technique was feasible for the integration of the bare die sensor on to the flex.

2.3 Network Protocol

The network protocol for the system is a customized design. It is designed to run on PIC/Atmel microcontrollers and written in C-Code. The structure of the protocol is based on a defined set of sentences all of which have a defined internal make-up. The protocol will be quite simple and power friendly. The Master is responsible for querying the slave nodes using a hard coded addressing system. Each slave can then react to the master query if it has been addressed. The slave modules will collect their information and relay it to the 25mm master, which will carry out some simple filtering and relay the information to the base station running software to control the environment.

2.4 RF Interface

The RF communication interface is being developed in parallel with the development of the core sensor system. The transceiver/microcontroller on the 25mm platform was developed to provide RF communications capability between sensor nodes. The layer incorporates a microcontroller driving a transceiver operating in the 2.4GHz ISM band. The embedded microcontroller is the ATMega128L, an 8-bit microcontroller with 128 Kbytes in-system programmable flash, allowing the implementation of the custom communication protocol described above. The 10mm RF cube is the result of a minimisation of the 25mm system using the exact same components. Any embedded routines developed and tested on the 25 mm module can then be ported to the 10mm platform for verification and characterisation of the minimised system. Figure 6 shows the initial design for the 10mm RF cube.

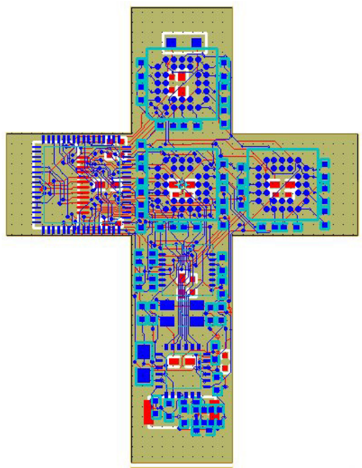

Figure 6. 10mm RF Cube

3 Testing

3.1 Bench Testing (25mm/Protocol)

There are many different modules in the system that had to be tested individually before the complete system was integrated. Each of the boards was tested and validated separately for sound electrical connection and signal integrity. The boards were then connected to the motherboard to test the system integration and power consumption. This testing proved successful and the system architecture was validated. The modules are currently in the specification and characterisation stages of testing.

The system protocol is being developed on a PIC platform using standard demonstration boards and development tools. This is to facilitate easy debugging in the development phase. The PIC controllers are hard wired currently and once developed will then be ported on to the 25mm Atmel microcontroller for testing with the RF Interface. The testing for the protocol is being carried out using an RS-323 bus set-up whereby the PICs can be plugged in alongside a PC to monitor network communications. The network currently consists of two slaves and a master.

3.2 10mm Flex Testing

The process for the 10mm integration is also being validated currently. Etching the circuit for the bare die MEMS devices showed that the initial landing pad design was too small and that an over etch of 70% was observed. This observation was made on features in the order of 110um x 110um. This required a redesign of the flex circuit with bigger feature sizes. The hole in the flex was manufactured by sandwiching the flex between two Pyrex sheets and drilling thought the entire structure. This eliminated the shredding effect on the flex, which was experienced in the earlier tests where the flex was just taped down to a planar surface. The tolerance of the hole position was ~ 50μm, which made drilling the holes very difficult, but after few trials good holes were formed as shown in Figure 7.

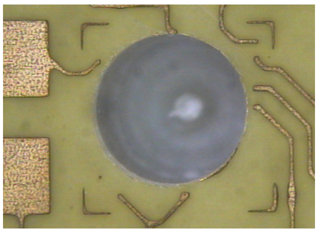

Figure 7. Processed Flex Circuit with drilled hole

4 Conclusion and Future Work

The work presented here has yielded a very powerful Inertial Measurement Unit structure to add to the existing sensor interfaces for the 25mm platform. The wireless networking functionality of the IMU allows for relatively easy deployment and will prove useful in areas other than wearable systems. Large-scale deployment for site monitoring in large industrial plants will find a wire free solution like this extremely beneficial.

In developing an easily deployable wireless network for the wearable domain it has yielded very important design and assembly parameters. A set of design rules has been developed for the integration of flex and bare die devices which will yield a more efficient design and assembly process in the future work carried out in this area.

The nest phase of the work includes the integration of the sensors and RF cubes in to a single module, the testing and characterisation of the Wireless link with our custom protocol and the integration of the modules into a wearable suit for application testing. Significant design challenges exist when reducing the RF module to a form factor of 10mm but work is under way in fabricating and characterising such a module. Initial suit designs involved the fabrication of a glove for proof of concept. The glove was constructed from a Lycra® material. The back of the glove is double sided so the flexible circuit could sit comfortably between the two layers. The glove was designed in this way to be aesthetic, comfortable and user-friendly. A Flat Flex Cable was used to interface the glove with the microcontroller board. The custom made glove can be seen below in Figure 9. The body suit proposed will consist of either an array of these Lycra® fixtures deployed around the body or a full body suit to deploy the sensors.

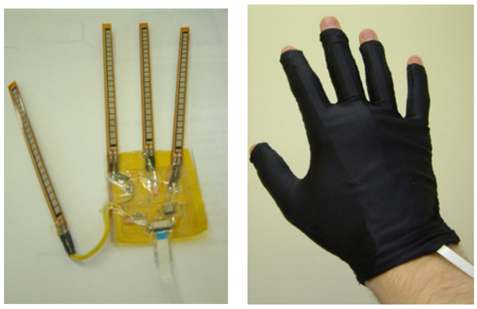

Figure 8. Sensor Flex Glove

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